

# Synthesis of Allenyl Esters by Horner-Wadsworth-Emmons Reactions of Ketenes Mediated by *i*-PrMgBr

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**Abstract:** The synthesis of conjugated allenyl esters (tri-substituted allenes) was achieved by the Mg(II)-mediated Horner-Wadsworth-Emmons reaction of methyl bis(2,2,2-trifluoroethyl)phosphonoacetate with di-substituted ketenes. In addition, a novel access to  $\alpha$ -fluorinated allenyl carboxamides (tetra-substituted allenes) is presented.

**Key words:** Horner-Wadsworth-Emmons reaction, allene, ketene, Grignard reagent, fluorine

Since the first synthesis of glutinic acid (allene-1,3-dicarboxylic acid) in 1887,<sup>1</sup> allenes have attracted considerable attention as chemical curiosities.<sup>2</sup> Furthermore, allene derivatives have recently been established as versatile building blocks in organic synthesis, including asymmetric synthesis.<sup>3</sup> Allenic structures are also found in natural products and pharmaceutical agents.<sup>4</sup> We have already established a characteristic method of synthesizing conjugated allenyl esters from diethyl  $\alpha$ -alkynyl- $\alpha$ -methoxy malonates via a cascade reaction,<sup>5</sup> and suggested the possibility of developing novel inhibitors of cysteine protease based on several biomimetic reactions using the conjugated allenyl compounds and their precursors.<sup>6</sup> On the other hand, the Horner-Wadsworth-Emmons (HWE) reaction of phosphonoacetates with aldehydes (or ketones) is one of the most useful methods of synthesizing  $\alpha,\beta$ -unsaturated esters.<sup>7</sup> There are, however, only a limited number of reports concerning the HWE reaction of ketene for the preparation of allenyl esters.<sup>8,9</sup> We now describe a facile one-pot synthesis of allenyl esters (tri- or tetra-substituted allenes) by HWE reactions of ketenes using *i*-PrMgBr as a base.

We first investigated HWE reactions of methyl bis(2,2,2-trifluoroethyl)phosphonoacetate (Still-Gennari reagent, **1**)<sup>10,11</sup> with a di-substituted ketene, which was prepared in situ from 2-phenylpropionyl chloride (**5a**) and triethylamine,<sup>12</sup> as shown in Table 1. Phosphonoacetate **1** is a typical *Z*-selective HWE reagent due to an electron-withdrawing effect of two trifluoroethoxy groups on its phosphorus atom. As expected, the desired conjugated allenyl ester **6a** (tri-substituted allene) was obtained by the HWE reaction of **1** in good to excellent yields using bases such as *n*-BuLi, NaH, and *i*-PrMgBr (Table 1, entries 1-3). Among these, *i*-PrMgBr afforded allenyl ester **6a** in an almost quantitative yield (98%).<sup>13,14</sup> We have already reported stereoselective HWE reactions for the preparation of  $\alpha,\beta$ -unsaturated esters using *i*-PrMgBr.<sup>15</sup> Thus, HWE reagents **2-4** were investigated

in the HWE reaction mediated by *i*-PrMgBr for the preparation of conjugated allenyl esters **6a** and **6a'** (Table 1, entries 4-6). As a result, *Z*-selective HWE reagent **2** (Ando reagent)<sup>16,17</sup> also furnished **6a'** in an excellent yield (96%). It appears that increasing the *Z*-selectivity of HWE reagents in the reaction with aldehydes and ketones tends to increase the chemical yields of allenyl ester **6a** (Table 1, entries 3, 5, 6).

**Table 1** HWE reactions of phosphonoacetates **1-4** with phenyl methyl ketene prepared in situ from 2-phenylpropionyl chloride (**5a**)

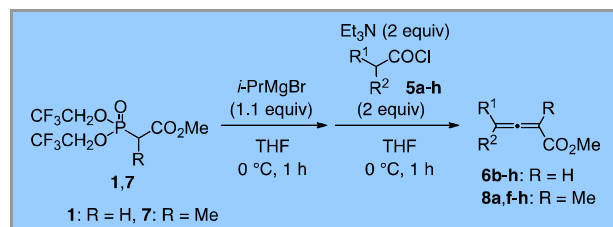
<p>1: R<sup>1</sup> = R<sup>2</sup> = CF<sub>3</sub>CH<sub>2</sub>, R<sup>3</sup> = Me            2: R<sup>1</sup> = R<sup>2</sup> = Ph, R<sup>3</sup> = Et            3: R<sup>1</sup> = CF<sub>3</sub>CH<sub>2</sub>, R<sup>2</sup> = Me, R<sup>3</sup> = Me            4: R<sup>1</sup> = R<sup>2</sup> = R<sup>3</sup> = Me</p>			
<p>6a: R<sup>3</sup> = Me            6a': R<sup>3</sup> = Et</p>			
Entry	HWE reagent	Base	Yield (%) <sup>a</sup>
1	<b>1</b>	<i>n</i> -BuLi	68 ( <b>6a</b> )
2	<b>1</b>	NaH	5 ( <b>6a</b> )
3	<b>1</b>	<i>i</i> -PrMgBr	98 ( <b>6a</b> )
4	<b>2</b>	<i>i</i> -PrMgBr	96 ( <b>6a'</b> )
5	<b>3</b>	<i>i</i> -PrMgBr	81 ( <b>6a</b> )
6	<b>4</b>	<i>i</i> -PrMgBr	72 ( <b>6a</b> )

<sup>a</sup> Isolated yields.

To explore the substrate scope of the HWE reaction, a range of in situ-generated ketenes from the corresponding acyl chlorides **5a-h** were subjected to reaction with HWE reagent **1** as shown in Table 2. In all cases investigated, HWE reactions of di-substituted ketenes derived from acyl chlorides **5b-e** proceeded smoothly to afford 90-100% yields of the desired allenyl esters **6b-e** (tri-substituted allenes) (Table 2, entries 1-4). On the other hand, the HWE reaction of mono-substituted ketenes derived from acyl chlorides **5f-h** resulted in the formation of allenyl esters **6f-h** (di-substituted allenes) in low yields (Table 2, entries

5-7). It is interesting to note that a similar HWE reaction of ketenes derived from **5f-h** with  $\alpha$ -methylated Still-Gennari reagent (**7**)<sup>18</sup> afforded the corresponding allenyl esters **8f-h** (tri-substituted allenes) in higher yields than those of **6f-h** (Table 2, entries 8-10). The HWE reaction of **7** with phenyl methyl ketene derived from acyl chloride **5a** furnished allenyl esters **8a** (tetra-substituted allene) in 89% yield (Table 2, entry 11).

**Table 2** HWE reactions of phosphonoacetates **1,7** with various ketenes prepared in situ from acid chlorides **5a-h**



Entry	HWE reagent	R <sup>1</sup>	R <sup>2</sup>	Yield (%) <sup>a</sup>
1	<b>1</b> (R = H)	Ph	Et	100 ( <b>6b</b> )
2	<b>1</b> (R = H)	Ph	Ph	100 ( <b>6c</b> )
3	<b>1</b> (R = H)	4-NO <sub>2</sub> Ph	Me	90 ( <b>6d</b> )
4	<b>1</b> (R = H)	4-MeOPh	Me	97 ( <b>6e</b> )
5	<b>1</b> (R = H)	Ph	H	29 ( <b>6f</b> )
6	<b>1</b> (R = H)	Bn	H	38 ( <b>6g</b> )
7	<b>1</b> (R = H)	<i>n</i> -C <sub>6</sub> H <sub>13</sub>	H	22 ( <b>6h</b> )
8	<b>7</b> (R = Me)	Ph	H	40 ( <b>8f</b> )
9	<b>7</b> (R = Me)	Bn	H	69 ( <b>8g</b> )
10	<b>7</b> (R = Me)	<i>n</i> -C <sub>6</sub> H <sub>13</sub>	H	65 ( <b>8h</b> )
11 <sup>b</sup>	<b>7</b> (R = Me)	Ph	Me	89 ( <b>8a</b> )

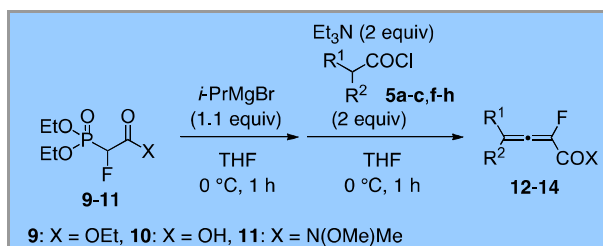
<sup>a</sup> Isolated yields.

<sup>b</sup> Reaction mixture was stirred for 3 h.

We next investigated the use of ethyl 2-fluoro-2-diethylphosphonoacetate (**9**)<sup>19,20</sup> in place of **1** as the HWE reagent in order to obtain a fluorinated allenyl ester. To the best of our knowledge, there are very few examples of the synthesis of  $\alpha$ -fluorinated allenyl esters.<sup>21</sup> As a result, the desired product **12a** (tetra-substituted allene) was obtained in moderate yield (Table 3, entry 1). However, the HWE reaction of phosphonoacetic acid **10** using a 2.1 equivalent of *i*-PrMgBr did not proceed at all (Table 3, entry 2). Finally, it appeared that the HWE reaction of Weinreb amide **11**<sup>22</sup> with di-substituted ketenes derived from acyl chlorides **5a-c** afforded fluorinated allenyl carboxamides **14a-c** (tetra-substituted allenes) in 71-100% yields (Table 3, entries 3-8).<sup>23</sup> Unfortunately, poor yields of fluorinated allenyl carboxamides **14f-h**

(tri-substituted allenes) were obtained in the HWE reaction of Weinreb amide **11** with mono-substituted ketenes derived from acyl chlorides **5f-h** (Table 3, entries 9-12).

**Table 3** HWE reactions of  $\alpha$ -fluorophosphonoacetates **9-11** with various ketenes prepared in situ from acid chlorides **5a-c,f-h**



Entry	HWE reagent	R <sup>1</sup>	R <sup>2</sup>	Yield (%) <sup>a</sup>
1	<b>9</b> (X = OEt)	Ph	Me	ca. 57 ( <b>12a</b> ) <sup>b</sup>
2 <sup>c</sup>	<b>10</b> (X = OH)	Ph	Me	0 ( <b>13a</b> )
3	<b>11</b> (X = N(OMe)Me)	Ph	Me	71 ( <b>14a</b> )
4 <sup>d</sup>	<b>11</b> (X = N(OMe)Me)	Ph	Me	90 ( <b>14a</b> )
5 <sup>e</sup>	<b>11</b> (X = N(OMe)Me)	Ph	Me	100 ( <b>14a</b> )
6	<b>11</b> (X = N(OMe)Me)	Ph	Et	71 ( <b>14b</b> )
7 <sup>e</sup>	<b>11</b> (X = N(OMe)Me)	Ph	Et	94 ( <b>14b</b> )
8	<b>11</b> (X = N(OMe)Me)	Ph	Ph	92 ( <b>14c</b> )
9	<b>11</b> (X = N(OMe)Me)	Ph	H	0 ( <b>14f</b> ) <sup>f</sup>
10	<b>11</b> (X = N(OMe)Me)	Bn	H	0 ( <b>14g</b> ) <sup>g</sup>
11 <sup>c</sup>	<b>11</b> (X = N(OMe)Me)	Bn	H	ca. 14 ( <b>14g</b> ) <sup>b,h</sup>
12	<b>11</b> (X = N(OMe)Me)	<i>n</i> -C <sub>6</sub> H <sub>13</sub>	H	0 ( <b>14h</b> ) <sup>i</sup>

<sup>a</sup> Isolated yields.

<sup>b</sup> Small amount of impurities were included.

<sup>c</sup> 2.1 equiv of *i*-PrMgBr was used.

<sup>d</sup> Reaction mixture was stirred for 3 h.

<sup>e</sup> Reaction mixture was stirred for 18 h.

<sup>f</sup> HWE reagent **11** was recovered (ca. 54%).

<sup>g</sup> HWE reagent **11** was recovered (ca. 40%).

<sup>h</sup> HWE reagent **11** was recovered (ca. 20%).

<sup>i</sup> HWE reagent **11** was not recovered.

In conclusion, we have developed a facile method of synthesizing conjugated allenyl esters **6** and **8** by the Mg(II)-mediated HWE reaction of **1** and **7** with di-substituted ketenes, which were prepared in situ from the corresponding acid chlorides. For the first time,  $\alpha$ -fluorinated allenyl carboxamides **14** have also been prepared successfully using the Mg(II)-mediated HWE reaction of **11** with di-substituted ketenes. We believe that the proposed method of synthesizing conjugated allenyl carboxylic acid derivatives is a valuable addition to the chemistry of allenes.

## Acknowledgment

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## Supporting Information

Supporting information for this article is available online at <http://>

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- (13) **Typical Procedure:** To a solution of methyl bis(2,2,2-trifluoroethyl)phosphonoacetate (**1**) (40  $\mu$ L, 0.188 mmol) in anhydrous THF (1.9 mL) was added *i*-PrMgBr (0.77 mol/L in THF, 269  $\mu$ L, 0.207 mmol), and the solution was stirred at 0 °C for 1 h under argon. After adding triethylamine (53  $\mu$ L, 0.377 mmol) and 2-phenylpropionyl chloride (**5a**) (56  $\mu$ L, 0.377 mmol), the mixture was stirred at 0 °C for 1 h under argon. The reaction mixture was treated with sat.  $\text{NH}_4\text{Cl}$  aq (2 mL) and then extracted with  $\text{CHCl}_3$  (20 mL x 3). The extract was dried over anhydrous  $\text{MgSO}_4$ , filtered, and concentrated in vacuo. The oily residue was purified by silica gel column chromatography [*n*-hexane–AcOEt (12.5:1 to 11:1)] to afford allenyl ester **6a** (34.7 mg, 98%).
- (14) The spectroscopic data of **6a** are as follows: Pale yellow oil;  $^1\text{H}$  NMR (500 MHz,  $\text{CDCl}_3$ )  $\delta$  2.21 (d,  $J$  = 2.9 Hz, 3H), 3.75 (s, 3H), 5.90 (q,  $J$  = 2.9 Hz, 1H), 7.27–7.28 (m, 1H), 7.33–7.40 (m, 4H);  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ )  $\delta$  16.2, 52.1, 89.5, 105.5, 126.2, 127.9, 128.6, 134.3, 166.1, 214.0; IR (neat) 2951, 1948, 1722, 1495, 1437, 1392, 1263, 1209, 1151  $\text{cm}^{-1}$ ; ESIMS  $m/z$ : calcd for  $\text{C}_{12}\text{H}_{12}\text{NaO}_2$  [ $\text{M}+\text{Na}$ ] $^+$ , 211.0735; found, 211.0732. Anal. Calcd for  $\text{C}_{12}\text{H}_{12}\text{O}_2$ : C, 76.57; H, 6.43. Found: C, 76.27; H, 6.54%.
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- (23) The spectroscopic data of **14a** are as follows: Yellow oil (37.6 mg, 100%);  $^1\text{H}$  NMR (500 MHz,  $\text{CDCl}_3$ )  $\delta$  2.35 (d,  $^3J_{\text{C,F}} = 8.3$  Hz, 3H), 3.26 (s, 3H), 3.51 (s, 3H), 7.31-7.40 (m, 3H), 7.49-7.53 (m, 2H);  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ )  $\delta$  18.3, 33.7, 61.6, 118.9 (d,  $^3J_{\text{C,F}} = 12.0$  Hz), 126.8 (d,  $^5J_{\text{C,F}} = 2.7$  Hz), 128.7, 129.1 (d,  $^6J_{\text{C,F}} = 1.7$  Hz), 129.6 (d,  $^1J_{\text{C,F}} = 234.8$  Hz), 134.4 (d,  $^4J_{\text{C,F}} = 1.7$  Hz), 162.0 (d,  $^2J_{\text{C,F}} = 40.1$  Hz), 193.2 (d,  $^2J_{\text{C,F}} = 18.7$  Hz); IR (neat) 2937, 1954, 1652, 1462, 1444, 1417, 1386, 1155  $\text{cm}^{-1}$ ; ESIMS  $m/z$ : calcd for  $\text{C}_{13}\text{H}_{14}\text{FNNaO}_2$   $[\text{M}+\text{Na}]^+$ , 258.0906; found, 258.0896. Anal. Calcd for  $\text{C}_{13}\text{H}_{14}\text{FNO}_2$ : C, 66.37; H, 6.00; N, 5.95. Found: C, 66.08; H, 6.02; N, 5.89%.

**Supporting Information**  
for  
**Facile Synthesis of Allenyl Esters by  
Horner-Wadsworth-Emmons Reactions of Ketenes Mediated by *i*-PrMgBr**

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**1. General Information**

**2. Experimental Procedures and Compound Characterizations**

**2.1 General procedure for the preparation of allenyl esters 6a-e, 8a,f-h**

**2.2 General procedure for the preparation of allenyl carboxamides 14a-c**

**3. NMR spectra**

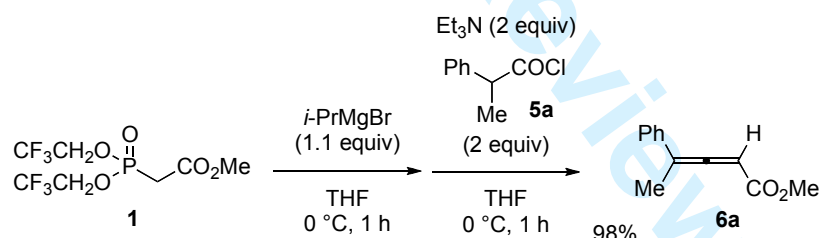
## 1. General Information

IR spectra were obtained using a JASCO FT/IR-6200 IR Fourier transform spectrometer.  $^1\text{H}$  NMR (500 MHz) and  $^{13}\text{C}$  NMR (125 MHz) spectra were recorded on a Bruker AV500 spectrometers. Chemical shifts are given in  $\delta$  values (parts per million) using tetramethylsilane (TMS) as an internal standard. Electron spray ionization mass spectra (ESIMS) were recorded on a Waters LCT Premier spectrometer. Elemental combustion analyses were performed using a J-SCIENCE LAB JM10. All reactions were monitored by TLC employing 0.25-mm silica gel plates (Merck 5715; 60  $F_{254}$ ). Column chromatography was carried out on silica gel [Kanto Chemical 60N (spherical, neutral); 63–210  $\mu\text{m}$ ]. Anhydrous THF was used as purchased from Kanto Chemical. Triethylamine was distilled prior to use. All other reagents were used as purchased.

## 2. Experimental Procedures and Compound Characterizations

### 2.1 General procedure for the preparation of allenyl esters 6a-e, 8a,f-h

#### Methyl 4-Phenylpenta-2,3-dienoate (6a)



To a solution of methyl bis(2,2,2-trifluoroethyl)phosphonoacetate (**1**) (40  $\mu\text{L}$ , 0.188 mmol) in anhydrous THF (1.9 mL) was added *i*-PrMgBr (0.77 mol/L in THF, 269  $\mu\text{L}$ , 0.207 mmol), and the solution was stirred at 0  $^\circ\text{C}$  for 1 h under argon. After adding triethylamine (53  $\mu\text{L}$ , 0.377 mmol) and 2-phenylpropionyl chloride (**5a**) (56  $\mu\text{L}$ , 0.377 mmol), the mixture was stirred at 0  $^\circ\text{C}$  for 1 h under argon. The reaction mixture was treated with sat.  $\text{NH}_4\text{Cl}$  aq (2 mL) and then extracted with  $\text{CHCl}_3$  (20 mL x 3). The extract was dried over anhydrous  $\text{MgSO}_4$ , filtered, and concentrated in vacuo. The oily residue was purified by silica gel column chromatography [*n*-hexane–AcOEt



(12.5:1 to 11:1)] to afford allenyl ester **6a** (34.7 mg, 98%). Pale yellow oil;  $^1\text{H}$  NMR (500 MHz,  $\text{CDCl}_3$ )  $\delta$  2.21 (d,  $J = 2.9$  Hz, 3H), 3.75 (s, 3H), 5.90 (q,  $J = 2.9$  Hz, 1H), 7.27-7.28 (m, 1H), 7.33-7.40 (m, 4H);  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ )  $\delta$  16.2, 52.0, 89.5, 105.5, 126.2, 127.9, 128.6, 134.2, 166.1, 214.0; IR (neat) 2951, 1948, 1722, 1495, 1437, 1392, 1263, 1209, 1151  $\text{cm}^{-1}$ ; ESIMS  $m/z$ : calcd for  $\text{C}_{12}\text{H}_{12}\text{NaO}_2$   $[\text{M}+\text{Na}]^+$ , 211.0735; found, 211.0732. Anal. Calcd for  $\text{C}_{12}\text{H}_{12}\text{O}_2$ : C, 76.57; H, 6.43. Found: C, 76.27; H, 6.54%.

#### Methyl 4-Phenylhexa-2,3-dienoate (**6b**)

Pale yellow oil;  $^1\text{H}$  NMR (500 MHz,  $\text{CDCl}_3$ )  $\delta$  1.18 (t,  $J = 7.3$  Hz, 3H), 2.50-2.63 (m, 2H), 3.75 (s, 3H), 5.97 (t,  $J = 3.4$  Hz, 1H), 7.25-7.28 (m, 1H), 7.33-7.40 (m, 4H);  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ )  $\delta$  12.2, 23.0, 52.0, 91.3, 112.4, 126.4, 127.8, 128.6, 134.1, 166.3, 213.7; IR (neat) 2970, 1945, 1720, 1592, 1495, 1453, 1436, 1398, 1258, 1209, 1151, 1032  $\text{cm}^{-1}$ ; ESIMS  $m/z$ : calcd for  $\text{C}_{13}\text{H}_{14}\text{NaO}_2$   $[\text{M}+\text{Na}]^+$ , 225.0891; found, 225.0889.

#### Methyl 4,4-Diphenylbuta-2,3-dienoate (**6c**)

Yellow oil;  $^1\text{H}$  NMR (500 MHz,  $\text{CDCl}_3$ )  $\delta$  3.78 (s, 3H), 6.10 (s, 1H), 7.33-7.38 (m, 10H);  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ )  $\delta$  52.2, 90.4, 114.2, 128.3, 128.7, 128.8, 134.2, 165.8, 214.7; IR (neat) 3420, 3058, 2950, 1942, 1723, 1493, 1435, 1386  $\text{cm}^{-1}$ ; ESIMS  $m/z$ : calcd for  $\text{C}_{17}\text{H}_{14}\text{NaO}_2$   $[\text{M}+\text{Na}]^+$ , 273.0891; found, 273.0871.

#### Methyl 4-(4-Nitrophenyl)penta-2,3-dienoate (**6d**)

Pale yellow oil;  $^1\text{H}$  NMR (500 MHz,  $\text{CDCl}_3$ )  $\delta$  2.25 (d,  $J = 2.8$  Hz, 3H), 3.78 (s, 3H), 6.00 (q,  $J = 2.8$  Hz, 1H), 7.53 (d,  $J = 8.8$  Hz, 2H), 8.21 (d,  $J = 8.8$  Hz, 2H);  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ )  $\delta$  16.1, 52.3, 90.5, 104.5, 123.9, 126.9, 141.3, 147.2, 165.3, 214.5; IR (neat) 2953, 1948, 1721, 1593, 1518, 1437, 1346, 1297, 1262  $\text{cm}^{-1}$ ; ESIMS  $m/z$ : calcd for  $\text{C}_{12}\text{H}_{11}\text{NNaO}_4$   $[\text{M}+\text{Na}]^+$ , 256.0586; found,

256.0577.

Methyl 4-(4-Methoxyphenyl)penta-2,3-dienoate (**6e**)

Pale yellow oil;  $^1\text{H}$  NMR (500 MHz,  $\text{CDCl}_3$ )  $\delta$  2.18 (d,  $J = 2.9$  Hz, 3H), 3.75 (s, 3H), 3.81 (s, 3H), 5.89 (q,  $J = 2.9$  Hz, 1H), 6.87-6.90 (m, 2H), 7.30-7.33 (m, 2H);  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ )  $\delta$  16.3, 52.1, 55.3, 89.4, 105.0, 114.0, 126.2, 127.4, 159.3, 166.3, 214.0; IR (neat) 2952, 2838, 2551, 2052, 1946, 1715, 1606, 1513, 1437, 1390, 1255, 1113  $\text{cm}^{-1}$ ; ESIMS  $m/z$ : calcd for  $\text{C}_{13}\text{H}_{14}\text{NaO}_3$   $[\text{M}+\text{Na}]^+$ , 241.0841; found, 241.0824.

Methyl 2-Methyl-4-phenylpenta-2,3-dienoate (**8a**)

Colorless oil;  $^1\text{H}$  NMR (500 MHz,  $\text{CDCl}_3$ )  $\delta$  1.97 (s, 3H), 2.17 (s, 3H), 3.73 (s, 3H), 7.23-7.25 (m, 1H), 7.34-7.38 (m, 4H);  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ )  $\delta$  15.2, 16.4, 52.2, 96.9, 103.6, 126.1, 127.4, 128.5, 135.5, 168.1, 211.4; IR (neat) 2989, 2952, 1947, 1715, 1598, 1494, 1436, 1372, 1207, 1191, 1120, 1067  $\text{cm}^{-1}$ ; ESIMS  $m/z$ : calcd for  $\text{C}_{13}\text{H}_{14}\text{NaO}_2$   $[\text{M}+\text{Na}]^+$ , 225.0891; found, 225.0882.

Methyl 2-Methyl-4-phenylbuta-2,3-dienoate (**8f**)

Pale yellow oil;  $^1\text{H}$  NMR (500 MHz,  $\text{CDCl}_3$ )  $\delta$  2.00 (d,  $J = 3.0$  Hz, 3H), 3.74 (s, 3H), 6.47 (q,  $J = 2.9$  Hz, 1H), 7.22-7.34 (m, 5H);  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ )  $\delta$  15.1, 52.3, 97.3, 99.1, 127.4, 127.7, 128.8, 132.4, 167.5, 212.4; IR (neat) 2951, 1949, 1716, 1435, 1274, 1122  $\text{cm}^{-1}$ .

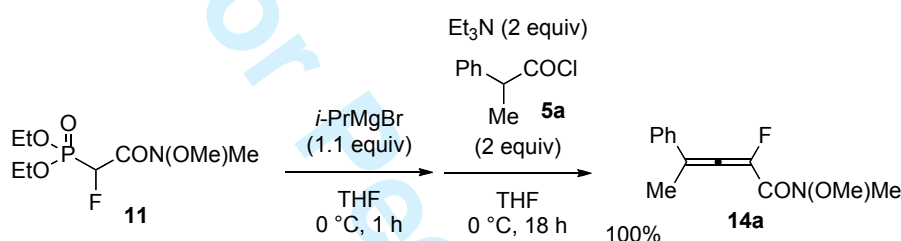
Methyl 2-Methyl-5-phenylpenta-2,3-dienoate (**8g**)

Colorless oil;  $^1\text{H}$  NMR (500 MHz,  $\text{CDCl}_3$ )  $\delta$  1.86 (d,  $J = 2.9$  Hz, 3H), 3.39-3.49 (m, 2H), 3.74 (s, 3H), 5.58-5.64 (m, 1H), 7.18-7.33 (m, 5H);  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ )  $\delta$  15.1, 34.7, 52.1, 93.3, 95.8, 126.5, 128.4, 128.5, 139.2, 168.2, 210.7; IR (neat) 2951, 1960, 1716, 1435, 1275, 1122  $\text{cm}^{-1}$ .



Methyl 2-Methyldeca-2,3-dienoate (**8h**)

Colorless oil;  $^1\text{H}$  NMR (500 MHz,  $\text{CDCl}_3$ )  $\delta$  0.89 (t,  $J = 6.8$  Hz, 3H), 1.23-1.39 (m, 6H), 1.40-1.47 (m, 2H), 1.86 (d,  $J = 2.9$  Hz, 3H), 2.10 (q,  $J = 7.1$  Hz, 2H), 3.73 (s, 3H), 5.43-5.48 (m, 1H);  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ )  $\delta$  14.1, 15.3, 22.7, 28.0, 28.6, 28.8, 31.6, 52.0, 93.9, 95.3, 168.5, 210.1; IR (neat) 2928, 2857, 1960, 1717, 1436, 1275, 1123  $\text{cm}^{-1}$ .

2.2 General procedure for the preparation of allenyl carboxamides **14a-c**2-Fluoro-*N*-methoxy-*N*-methyl-4-phenylpenta-2,3-dienamide (**14a**)

To a solution of diethyl {1-fluoro-2-[methoxy(methyl)amino]-2-oxoethyl}phosphonate (**11**) (40.0 mg, 0.156 mmol) in anhydrous THF (1.6 mL) was added *i*-PrMgBr (0.74 mol/L in THF, 231  $\mu\text{L}$ , 0.171 mmol), and the solution was stirred at 0 °C for 1 h under argon. After adding triethylamine (43  $\mu\text{L}$ , 0.311 mmol) and 2-phenylpropionyl chloride (**5a**) (46  $\mu\text{L}$ , 0.311 mmol), the mixture was stirred at 0 °C for 18 h under argon. The reaction mixture was treated with sat.  $\text{NH}_4\text{Cl}$  aq (5 mL) and then extracted with  $\text{CHCl}_3$  (50 mL x 3). The extract was dried over anhydrous  $\text{MgSO}_4$ , filtered, and concentrated in vacuo. The oily residue was purified by silica gel column chromatography [ $\text{CHCl}_3$ –AcOEt (50:1)] to afford  $\alpha$ -fluorinated allenyl carboxamide **14a** (37.6 mg, 100%). Yellow oil;  $^1\text{H}$  NMR (500 MHz,  $\text{CDCl}_3$ )  $\delta$  2.35 (d,  $^5J_{\text{C,F}} = 8.3$  Hz, 3H), 3.26 (s, 3H), 3.51 (s, 3H), 7.31-7.40 (m, 3H), 7.49-7.53 (m, 2H);  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ )  $\delta$  18.3, 33.6, 61.6, 118.9 (d,  $^3J_{\text{C,F}} = 12.0$  Hz), 126.8 (d,  $^5J_{\text{C,F}} = 2.7$  Hz), 128.7, 129.1 (d,  $^6J_{\text{C,F}} = 1.7$  Hz), 129.6 (d,  $^1J_{\text{C,F}} = 234.8$  Hz), 134.4 (d,  $^4J_{\text{C,F}} = 1.7$  Hz), 162.0 (d,  $^2J_{\text{C,F}} = 40.1$  Hz), 193.2 (d,  $^2J_{\text{C,F}} = 18.7$  Hz); IR (neat) 2937, 1954, 1652, 1462, 1444, 1417, 1386, 1155  $\text{cm}^{-1}$ ; ESIMS  $m/z$ : calcd for  $\text{C}_{13}\text{H}_{14}\text{FNNaO}_2$  [ $\text{M}+\text{Na}$ ] $^+$ , 258.0906;

found, 258.0896. Anal. Calcd for  $C_{13}H_{14}FNO_2$ : C, 66.37; H, 6.00; N, 5.95. Found: C, 66.08; H, 6.02; N, 5.89%.

2-Fluoro-*N*-methoxy-*N*-methyl-4-phenylhexa-2,3-dienamide (**14b**)

Yellow oil;  $^1H$  NMR (500 MHz,  $CDCl_3$ )  $\delta$  1.23 (t,  $J = 7.3$  Hz, 3H), 2.63-2.79 (m, 2H), 3.25 (s, 3H), 3.48 (s, 3H), 7.30-7.40 (m, 3H), 7.49-7.53 (m, 2H);  $^{13}C$  NMR (125 MHz,  $CDCl_3$ )  $\delta$  12.0 (d,  $^5J_{C,F} = 1.8$  Hz), 25.0, 33.7, 61.5, 125.9 (d,  $^3J_{C,F} = 12.1$  Hz), 126.9 (d,  $^5J_{C,F} = 2.6$  Hz), 128.8, 129.1 (d,  $^6J_{C,F} = 1.7$  Hz), 132.2 (d,  $^1J_{C,F} = 234.6$  Hz), 134.3 (d,  $^4J_{C,F} = 1.7$  Hz), 162.2 (d,  $^2J_{C,F} = 40.2$  Hz), 192.8 (d,  $^2J_{C,F} = 18.8$  Hz); IR (neat) 2972, 2937, 1950, 1660, 1456, 1384, 1153  $cm^{-1}$ ; ESIMS  $m/z$ : calcd for  $C_{14}H_{16}FNNaO_2$   $[M+Na]^+$ , 272.1063; found, 272.1061. Anal. Calcd for  $C_{14}H_{16}FNO_2$ : C, 67.45; H, 6.47; N, 5.62. Found: C, 67.16; H, 6.54; N, 5.47%.

2-Fluoro-*N*-methoxy-*N*-methyl-4,4-diphenylbuta-2,3-dienamide (**14c**)

Yellow oil;  $^1H$  NMR (500 MHz,  $CDCl_3$ )  $\delta$  3.28 (s, 3H), 3.40 (s, 3H), 7.38-7.42 (m, 6H), 7.44-7.47 (m, 4H);  $^{13}C$  NMR (125 MHz,  $CDCl_3$ )  $\delta$  33.7, 61.7, 125.6 (d,  $^3J_{C,F} = 12.1$  Hz), 128.7, 129.1 (d,  $^5J_{C,F} = 3.1$  Hz), 129.2, 131.0 (d,  $^1J_{C,F} = 235.1$  Hz), 134.7, 161.5 (d,  $^2J_{C,F} = 39.9$  Hz), 195.6 (d,  $^2J_{C,F} = 19.2$  Hz); IR (neat) 2936, 1945, 1660, 1444, 1385, 1155  $cm^{-1}$ ; ESIMS  $m/z$ : calcd for  $C_{18}H_{16}FNNaO_2$   $[M+Na]^+$ , 320.1063; found, 320.1060.

## 3. NMR spectra

